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Enclosure 1

## Statement of the Problem Studied

**Summary of proposed work, from original proposal:** It is proposed to research topics with an optimal composition of technology, physics, and applications overlapping these areas to the extent possible. Pulsed Power is essentially a unifying enabling technology. Basic plasma research is necessary in not only pulsed power, but also in the pollution remediation and combustion-ignition areas. The application of fields to cells (and tumors) is enabled by new pulsed power technology, and is interdisciplinary with researchers in the life sciences, biology, medicine and biomedical engineering.

## Summary of the Most Important Results

Scientific progress lies in three areas: Pulsed power, transient plasma ignition, and applications of pulsed power to biology. We report here 1) Significant progress in the application of transient plasma to ignition, and 2) Significant progress in the study of the effects of nanosecond pulsed electric fields on biological cells. The work in transient plasma ignition and bioelectrics is summarized each on a separate page.

These diverse areas lie within the study of pulsed power and its applications, and although very diverse, do fall within the scope of the original proposed work (summary reprinted below). The projects described have also received significant support from the AFOSR and the ONR.

### Progress in SiC Pulsed Power Switch Research

Because of its larger bandgap energy and higher electron mobility in comparison with 6H-SiC, the SiC polytype 4H-SiC is a promising semiconductor material for applications to pulsed power technology. Pulsed power applications simultaneously require high blocking voltage, high peak current, fast turn-on, and low forward drop. However, poor oxide quality and oxide breakdown have thus far limited the performance of 4H-SiC MOSFETs, and the high breakdown field strength of SiC as high as  $\sim 3\text{MV/cm}$  has not been fully exploited. To address these issues, we have during the previous year initiated studies of the high dielectric materials  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  of Metal-Insulator-SiC (MIS) structures as possible gate dielectrics for SiC devices.  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  were chosen because of their high dielectric constants and bandgap energies as well as because of the acceptance of Ti and Al in most modern CMOS fabrication facilities. Nitridation technology has been widely used in Si device fabrication to improve the interface quality and prevent the formation of an interfacial layer of  $\text{SiO}_2$  by annealing Si in a NO ambient. For comparison, we have applied this technology to the interface between the insulator and the SiC MIS structure. MIS capacitors (Fig.1) have been fabricated to evaluate whether  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  deposited by E-beam evaporation truly have potential as gate dielectrics in pulsed power SiC devices [1].

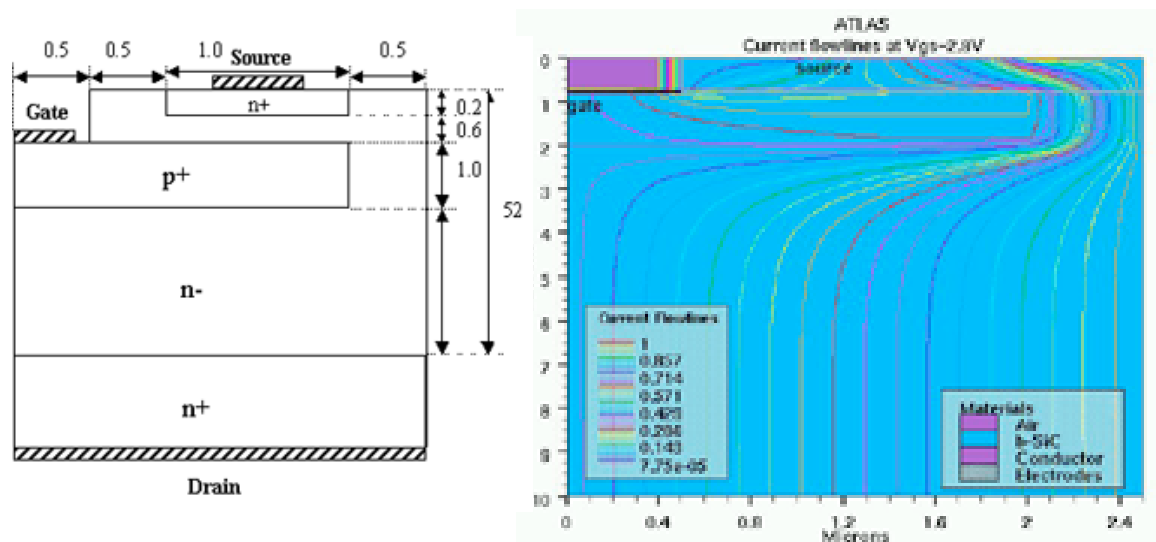


Fig. 1. Schematic of a half-cell of the 4H-SiC VJFET (Distances are in micrometers).  
 Right: ATLAS simulation of current flow in gate region.

1) This work was reported at the IEEE 2004 Power Modulator Conference, San Francisco CA, May 23-26 2004. "Investigation of 4H-SiC MIS Capacitors with TiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> as Gate Insulators," Qiong Shui, Michael S. Mazzola, Xianyue Gu, M.A. Gundersen, and Charles W. Myles.

## Transient plasma ignition

Transient (true non-thermal, 30 to 100 nsec) plasma discharges have been investigated as a potential new method for flame and pulse detonation engine (PDE) ignition. Experimental results show that transient plasma discharge results in shorter ignition delay and pressure rise time (typically by a factor of 3 for CH<sub>4</sub>/Air quiescent mixture, and even more for flowing pulse detonation engine ethane-air mixtures). Further benefits include higher maximum pressure indicative of improved efficiency. Pulse energies were typically 50 mJ to 1 J, demonstrating low energy required, comparable to traditional spark ignition. We conducted experiments in quiescent fuel air mixtures including methane, ethane, propane, butane and octane for various equivalence ratios.

We observed

- improved ignition with reduced delays and improved combustion efficiencies in various fuel-air mixtures,
- improved PDE ignition (through ONR support in studies at the NPS, with partial AFOSR support).

A diagram of experimental apparatus for quiescent studies is shown in Figure 2. Additional figures are included as an attachment (Appendix I). Reports have been presented at several technical meetings, and published in AIAA Proc. [2] (see also attached list of presentations and publications).

In all cases significant modification of initial combustion chemistry appears to be occurring, leading to more effective combustion over a wider range of parameters, such as pressure and fuel composition.

Based on studies of quiescent fuel mixtures at USC, off campus studies of pulse detonation engine (PDE) ignition at the Naval Postgraduate School (NPS), and initial studies of transient plasma enhanced radical production in collaboration with the U. Cincinnati, (UC) we conclude that transient plasma has strong potential for improved ignition, flameholding, and combustion enhancement.

Future work is planned to specifically delineate the production and effect of key species. Collaborations are planned that, if support is available, will address diagnosis, fuel mixing strategies, and theoretical support necessary to develop fundamental understanding and provide a pathway to implementation. This work also received support from the AFOSR (Dr. Julian Tishkoff) and the ONR (Dr. Gabriel D. Roy).

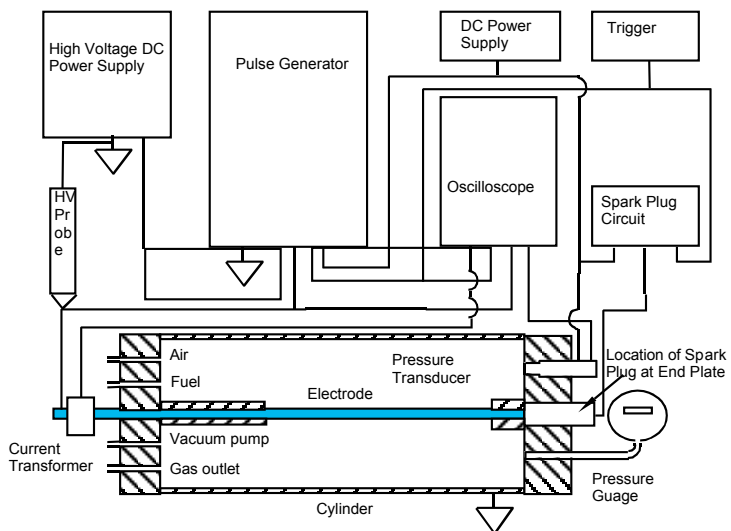
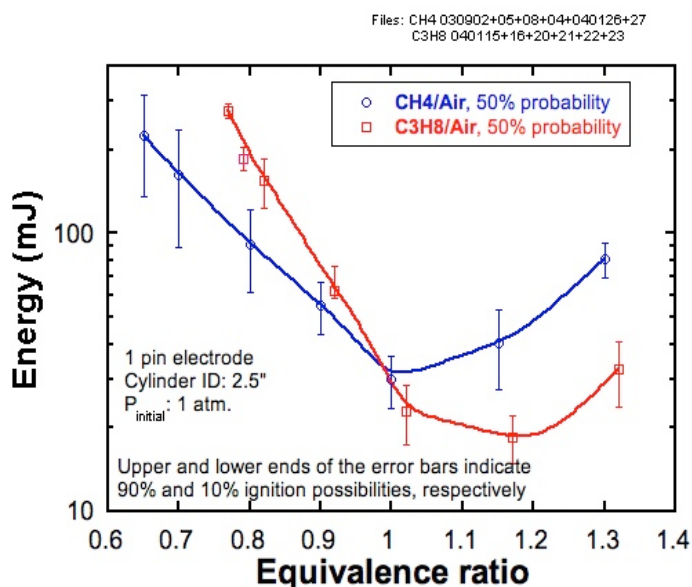


Figure 2. Apparatus for quiescent fuel mixture studies. Pulse generator employs either thyatron (100 nsec or longer pulses) or pseudospark (50 nsec pulses).



In Appendix I several slides which illustrate some of the experimental situations are presented. These include further detail of the quiescent and the PDE experimental arrangements, an example of typical data from quiescent studies. The difference between a transient plasma streamer array, and an arc, is shown graphically.

Figure 3. Plot showing minimum ignition energy for methane-air and propane-air mixtures, well under 100 mJ. This is indicative of the energy efficiency, and the low energy cost, implicit in this approach.

The transient plasma results suggest several future directions. This appears to be promising for a variety of ignition situations, and it would be valuable to explore further new applications. This is because data collected in quiescent and flowing mixtures shows substantial improvement in conditions for ignition (such as not requiring additional oxygen for a PDE, and reducing ignition delays in PDE to the point that substantially higher repetition rates may be envisaged). An improved understanding of the transient plasma physics, including contributions from theory, would be valuable in providing a basis for understanding.

2) J.B. Liu, P.D. Ronney, F. Wang, L.C. Lee, and M.A. Gundersen, "Transient Plasma Ignition For Lean Burn Applications," Proceedings of 2003 American Institute of Aeronautics and Astronautics, 41st Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 2003, No. 2003-6208; See also J.B. Liu, P.D. Ronney, and M. Gundersen, "Premixed Flame Ignition by Transient Plasma Discharges," Proceedings of the Third Joint Meeting of the U.S. Sections of the Combustion Institute, Chicago, Illinois, March 16-19, 2003, Paper B-25. Several papers related to this work were presented at the 2004 AIAA Reno meeting, and are listed as an attachment.

### **Observation of Field Dependent Electroperturbation of Jurkat-T Lymphoblasts**

The most important results during the past year which have been published or accepted for publication in refereed journals are in the area of "bio-nano-electrics", that is, in the study of the effects of intense electric fields applied for very short times to biological cells (typically Jurkat-T lymphoblasts, a human cancer cell). These results were primarily supported by funding from the AFOSR, and were supplemented with ARO support, partly because of the importance that we attach to this new research direction and the data that is emerging.

In Figure 4 is shown the effect of a 30 nsec, 2.5 MV/m (averaged over cuvette electrode separation) on a Jurkat cell (approx. 10 micron size). Evident in the upper right cell, after applying the nano-pulsed field, are intracellular elements, which are fluorescing due to Calcium release (probably from the endoplasmic reticulum). This demonstrates the penetration of the electric field into the interior of the cell, and that the field affects internal cell organelles.

We were able to observe real-time imaging of calcium bursts in human lymphocytes exposed to nanosecond, megavolt-per-meter pulsed electric fields. Ultra-short (less than 30 ns), high-field (greater than 1 MV/m), electric pulses induce increases in cytosolic calcium concentration and translocation of phosphatidylserine (PS) to the outer layer of the plasma membrane in Jurkat T lymphoblasts. Pulse-induced calcium bursts occur within milliseconds and PS externalization within minutes. Caspase activation and other indicators of apoptosis follow these initial symptoms of nanosecond pulse exposure. Pulse-induced PS translocation is observed even in the presence of caspase inhibitors. Ultra-short, high-field, electroperturbative pulse effects differ substantially from those associated with electroporation, where pulses of a few tens of kilovolts-per-meter lasting a few tens of microseconds open pores in the cytoplasmic membrane. Nanosecond pulsed electric fields, because their duration is less than the plasma membrane charging time, develop voltages across intracellular structures without porating the cell [3].

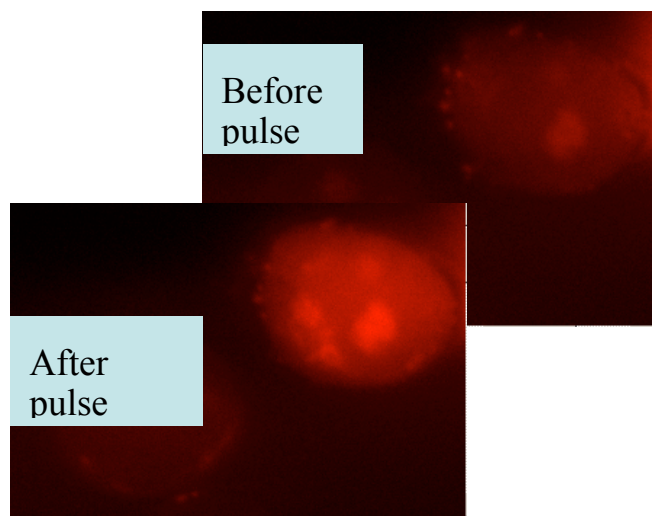


Figure 4. Observation of  $\text{Ca}^{2+}$  fluorescence with Rhod-2 dye following application of 2.5 MV/m electric field. 1 pulse at 0 seconds, then 4 pulses at 7 seconds.

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**Papers published in non-peer-reviewed journals or in conference proceedings:**

Kuthi, A., Liu, J., Ronney, P. D., and Gundersen, M. A., "Premixed Flame Ignition By Pulsed Corona Discharges," Western States Section, The Combustion Institute, 2002 Spring Meeting, March 25-26, 2002.

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F. Wang, A. Kuthi, and M.A. Gundersen, "Technology for Transient Plasma Ignition," 17<sup>th</sup> ONR Propulsion Meeting, Cambridge, MA, June 16-18, 2004.

**Papers presented at meetings, but not published in conference proceedings:**

A. Kuthi, P. Gabrielson and M. Gundersen, "Marx Generator Using Dense Plasma Switches," 31<sup>st</sup> IEEE International Conference on Plasma Science, June 28-July 1, 2004, Baltimore, MD.

A. Kuthi and M. Gundersen, "Simple Model of Pseudospark discharge Initiation," 31<sup>st</sup> IEEE International Conference on Plasma Science, June 28-July 1, 2004, Baltimore, MD.

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“Compact pulse generator for nanosecond electroperturbation of biological cells,” Gu, X., A. Kuthi, M. Behrend, P. T. Vernier, Q. Zhou, and M. A. Gundersen, IEEE 26<sup>th</sup> International Power Modulator Conference, San Francisco, 2004.

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“Real-time imaging of mammalian cells in nanosecond, megawatt, millijoule pulsed electric fields,” Vernier, P. T., L. Marcu, Y. Sun, S. Salemi, C. M. Craft, and M. A. Gundersen, BiOS 2004 (SPIE), San Jose, 2004.

“Nanosecond pulsed electric fields trigger intracellular signals in human lymphocytes,” Vernier, P. T., Y. Sun, L. Marcu, C. M. Craft, and M. A. Gundersen, Nanotech 2004, Boston, 2004.

“Nanoelectropulse perturbations of calcium and phospholipid distribution in human lymphocytes,” Vernier, P. T., Y. Sun, L. Marcu, C. M. Craft, and M. A. Gundersen, Bioelectromagnetics Society 26<sup>th</sup> Annual Meeting, Washington, 2004.

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“Non-invasive approaches to nano-biology through advanced pulsed power,” Y. Sun, P. T. Vernier, M. Behrend, L. Marcu, and M. A. Gundersen, Workshop on High-Field Effects and Fast Pulse Responses in Bio-Systems, IEEE Conference on Electrical Insulation and Dielectric Phenomena, October 19-22, Albuquerque, 2003.

### **Manuscripts submitted, but not published:**

### **List of Participating Scientific Personnel:**

Professor M. Gundersen	Professor/Department Chair
Dr. Andras Kuthi	Research Scientist
Dr. Jianbang Liu	Research Associate Professor
Ms. Xianyue Gu	Graduate Research Assistant
Mr. Matthew Behrend	Undergraduate Research Assistant
Ms. Qiong Shui	Graduate Research Assistant
Mr. Fei Wang	Graduate Research Assistant
Dr. Chunqi Jiang	Postdoctoral Research Associate
Dr. P. Thomas Vernier	Ph.D. – June 2004
Mr. Clayton Young	Graduate Research Assistant
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### **Report of Inventions (by title only):**

Method for Intracellular Modifications within Living Cells using Pulsed Electric Fields, (USC017.003A), filed pursuant to U.S. Provisional No. 60/336,587